Nonlinear Internal Waves: Test of the Inverted Echo Sounder

David M. Farmer
Graduate School of Oceanography (educational)
University of Rhode Island
Narragansett, RI 02882
Phone: (401) 874-6222 fax (401) 874-6889 email: dfarmer@gso.uri.edu

Award Number: N00014-05-1-0286

LONG-TERM GOALS

Develop, through comprehensive observation, a physics based understanding of nonlinear internal wave [NLIW] generation and evolution applicable to a broad range of environments and the corresponding relationship to the internal tide. Develop through observations a robust relationship between subsurface features of NLIW and their surface remote sensing expression (especially SAR).

OBJECTIVES

To acquire observations of nonlinear internal waves in the South China Sea, using modified pressure sensor equipped inverted echo sounders [PIES]. The deployments will test the applicability of this technique and explore approaches for inverting the data to recover internal wave properties.

APPROACH

Our approach made use of two modified PIES deployed close to S Ramp's thermistor string moorings in the South China Sea (Figure 1) during the period August-October 2006. The juxtaposition of the measurements with the thermistor moorings allowed direct comparison of the inversion procedure and a test of the overall reliability of inverted echo sounders for observing nonlinear internal waves and data inversion using nonlinear internal wave models. In addition our approach included acquisition of a limited data set in which detection and digitization of the raw acoustic signal coulod be used to examine the way in which the present instrument design converts this signal to a single integral travel time measurement and to develop improved signal processing approaches. Instrument modifications were carried out by Gerry Chaplin (URI) and the deployments by Erran Sousa (URI) in conjunctionwith Steve Ramp (NPGS). Randy Watts (URI) and his team carried out a second deployment of a PIES with broad band digitization. Jae-Hun Park (URI) and student student Li Qiang (URI) took part in the data analysis. Chris Jackson (GOA) identified MODIS images applicable to the deployment period.

WORK COMPLETED

Two PIES were modified for rapid (6s) sampling and deployed at P1 and P2 in the South China Sea, close to Ramp's thermistor moorings B1 and B2. (Figure 1). Following instrument recovery the data were processed to derive time series of the acoustic echo propagation delay and inverted to derive vertical displacements of streamlines using linear and nonlinear models. A further brief deployment of a PIES modified for broad band recording of the raw acoustic signal was also made.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**
4. TITLE AND SUBTITLE **Nonlinear Internal Waves: Test of the Inverted Echo Sounder**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Rhode Island,Graduate School of Oceanography,Narragansett,RI,02882**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

RESULTS

It was demonstrated that PIES time series clearly reveal the passage on nonlinear internal waves as well as other features, including passage of a nearby typhoon. Analysis of the observed signals in conjunction with remote sensing images and nearby thermistor data shows that the shape and wave speed of the observed waves was generally consistent with the fully nonlinear DJL model. Detailed comparison of the predicted streamline deformation calculated for isolated waves was similar to, but slightly narrower than, thermistor string observations. The broad band surface scattering measurements provide a data base for testing the signal processing approach used in the current version of the PIES instruments.

The return acoustic travel time does not always correspond to the first arrival, due to interference from multiple surface facets which delay the detected travel time. The probability distribution for an observed time series has a maximum close to the earliest possible arrival time which decays rapidly with increasing delay (Figure 2). Lacking detailed surface scatter analysis we found that a useful initial approach involved grouping the data into 1 minute intervals and taking the first arrivals only. The resulting time series (Figure 3) show the presence of an internal tide, together with high frequency wave packets in the troughs of the internal tide. Expanding a small segment of the data (Figure 4) reveals the shape and range of individual waves.

As an initial step towards analyzing these data, the Dubreil-Jacotin-Long [DJL] model was fitted, for the nominal density profile at deployment obtained by CTD during deployment. The best fit to the observed amplitude then yields a wave speed (~3.0ms-1) and a predicted streamline deformation as a function of depth. Wave speeds close to DJL predictions were found using travel times between moorings and also for observed positions in MODIS images. PIES inferred NLIW shapes also match predictions quite well (Figure 5). Comparison of streamline deformations with the thermistor chain data also show reasonable similarity, although the DJL inversion of PIES data leads to a somewhat narrower wave than the moored data. Possible explanations include mooring motion induced by the passing wave and failure to include the internal tide in this preliminary inversion approach.

Attempts to calculate the time at which the NLIW were first launched from Luzon Strait by back-propagation towards the generation area indicate that a deepening of the stratification must be included in the eastern portion of the South China Sea to arrive at realistic launch conditions associated with an ebb tide. While the details of the generation mechanism have yet to be resolved, deeper stratification, and hence higher NLIW speeds can be expected to occur towards Luzon Strait in the presence of Kuroshio incursion into the South China Sea.

The PIES records also reveal a period of several hours of significant increase in acoustic travel time, on August 12 caused by shoaling of the stratification, associated with passage of tropical cyclone Sanvu above the instrument deployed at P1 (Figure 6). The resulting time series from PIES deployments thus illustrate the potential of such measurements to monitor upper ocean processes over a range of scales including NLIW, the barotropic tide, the internal tide, slowly varying stratification associated with meso-scale variability (which is the classical application of this measurement approach) and extreme meteorological effects. Finally, our broad band measurements of the surface scatter provide highly resolved time series of acoustic arrivals from each transmitted pulse, providing a

data set with which to examine the detailed character of the surface scatter. Such measurements will lead to improved signal processing approaches and may shed light on sea surface conditions.

IMPACT/APPLICATIONS

Our observations have demonstrated the potential for low cost acquisition of time series of nonlinear internal waves, internal tides and other upper level processes with time scales of minutes to hours, thus extending the range of ocean phenomena accessible by this measurement technique. The lower cost of the deployment makes it feasible to consider 2D arrays for the study of effects due to variable topography and radial spreading that would be impractical with higher cost moorings.

RELATED PROJECTS

This project is closely related to a study of breaking nonlinear internal waves, in which instabilities observed in near surface NLIW are being analyzed with the help of highly resolved numerical models.

HONORS/AWARDS/PRIZES

Elected Fellow of the Royal Society of London. (D Farmer, University of Rhode Island.)

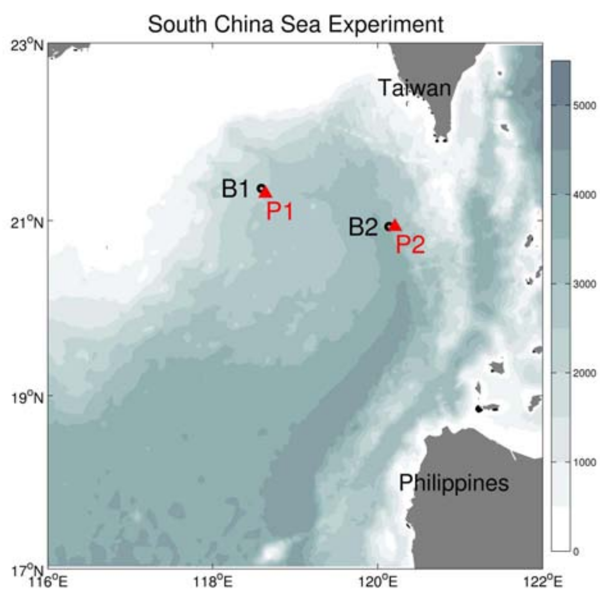

Figure 1. Chart showing locations of two PIES deployments P1, P2 adjacent to S Ramp's thermistor string moorings B1, B2.

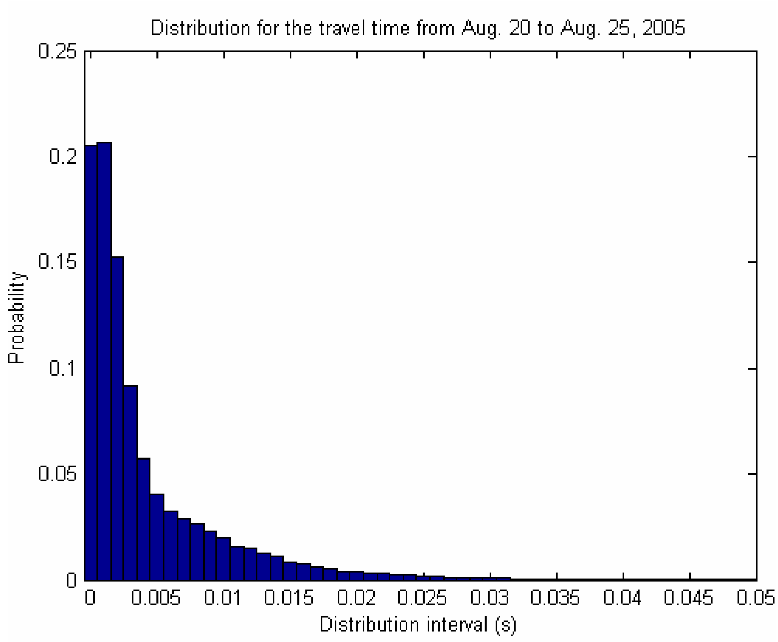

Figure 2. Probability distribution for the arrival time of an echo from the sea surface. The delay is referenced to the time of the earliest arrival in an ensemble of successive groups of ten transmissions.

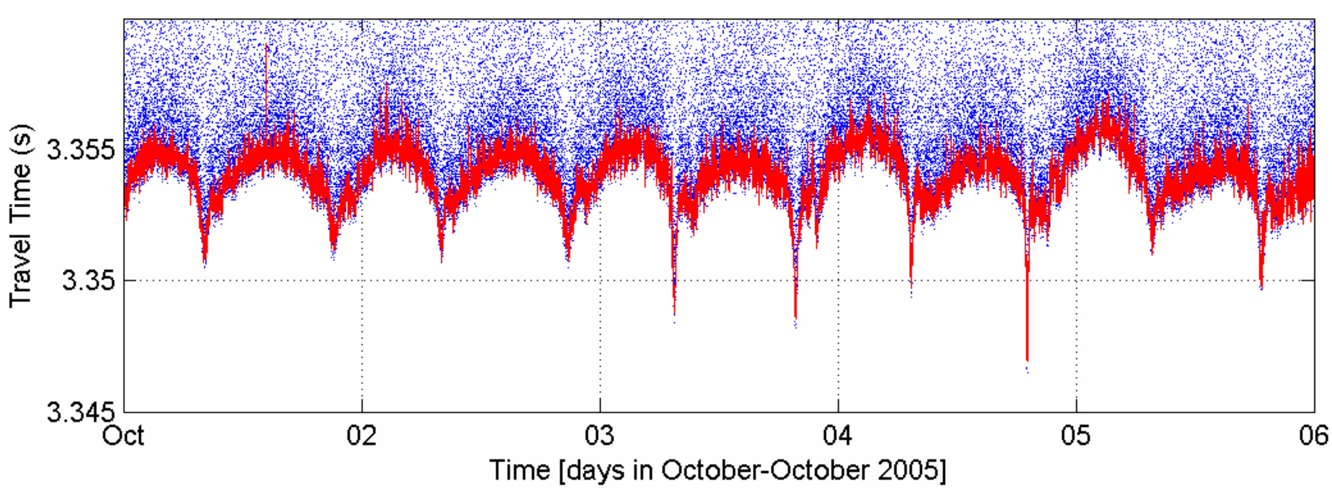

Figure 3. Time series of measurements of acoustic echo delay for PIES operating at P1, illustrating internal tide and presence of NLIW in the wave troughs. Greater time delays correspond to shallower stratification.

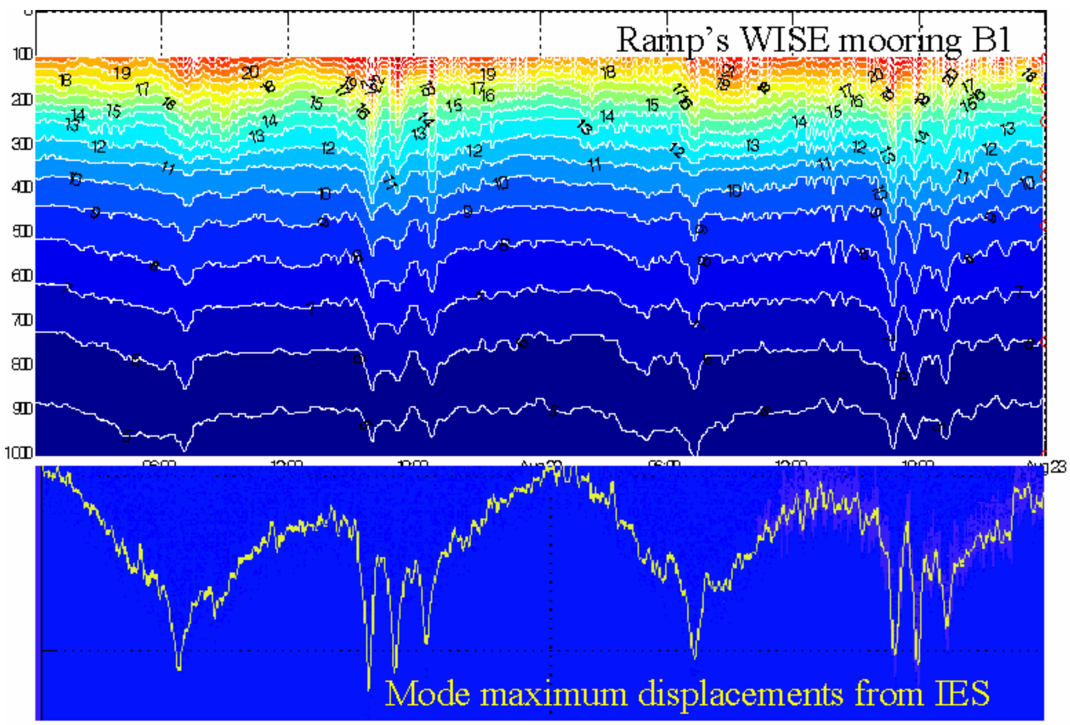

Figure 4. Upper panel: Temperature contours from Ramp's thermistor string at P1. Lower panel: Time series from PIES for same period showing internal tide and NLIW. Vertical displacement calculated from Mode 1 internal wave; vertical spacing between dotted lines in lower panel is 120m.

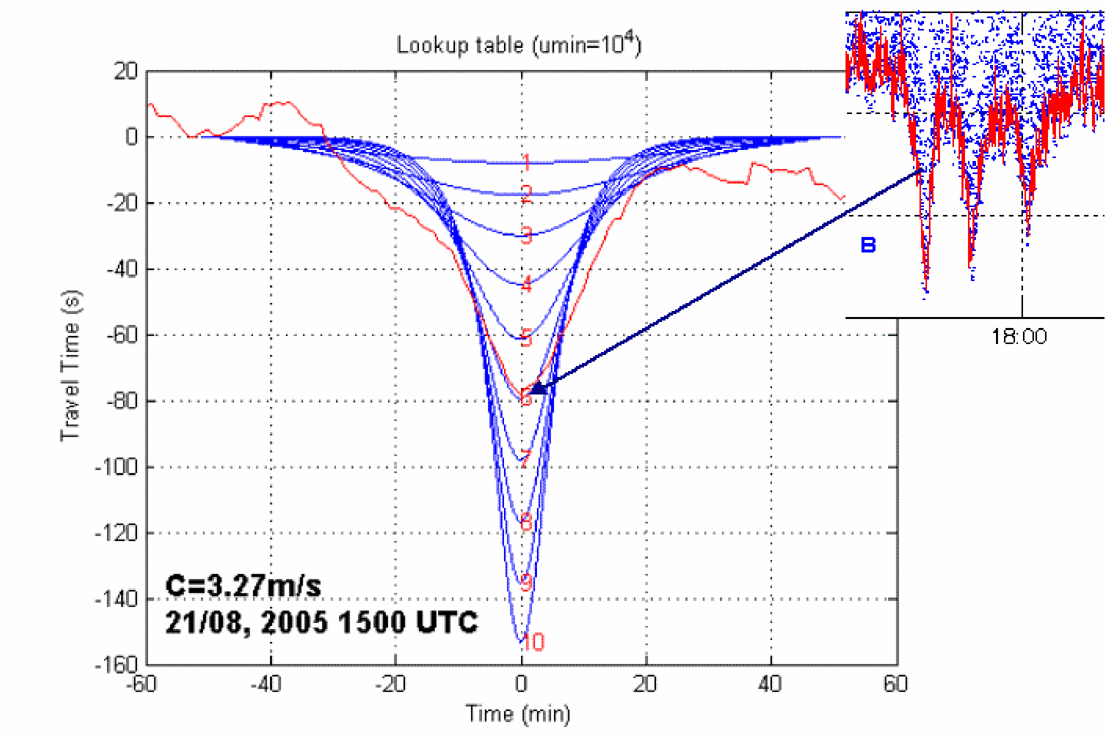

Figure 5. NLIW eigenmode maximum displacement time series is fitted to Dubreil-Jacotin-Long model. The model then yields wave speed and streamline displacement as function of depth.

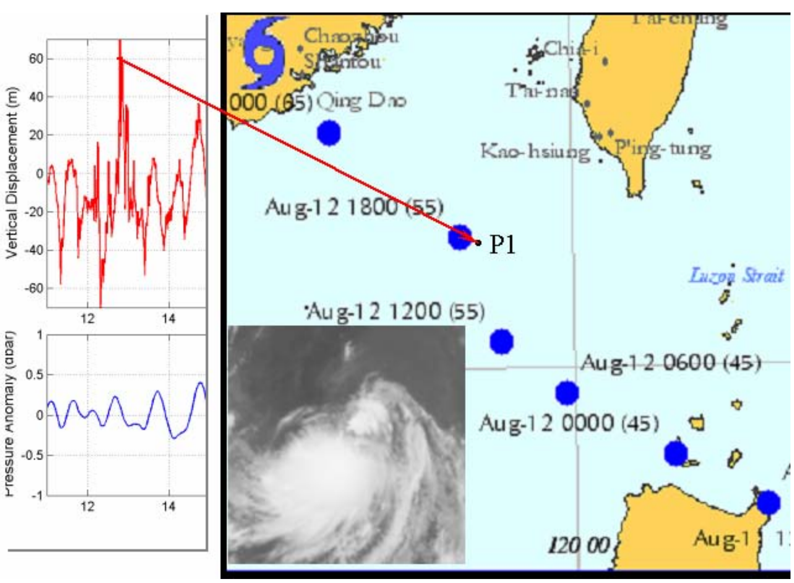

Figure 6. Left: Time series of inferred vertical eigenmode maximum displacement. Right: Locations of tropical Sanvu as it crossed the South China Sea. Large vertical displacement occurs as Sanvu passes over P1.